North Pacific Acoustic Laboratory

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LONG-TERM GOALS

The ultimate limits of long-range sonar are imposed by ocean variability and the ambient sound field. Scattering from internal waves limits the temporal and spatial coherence of the received signal. Low frequency noise is dominated by shipping and by wave-breaking processes. The resulting “granularity” of the noise field can be exploited for detection and localization purposes. Our long-term objective is to understand the fundamental limits to signal processing imposed by these ocean processes, to enable advanced signal processing techniques, including matched field processing and other adaptive array processing methods, to capitalize on the three-dimensional character of the sound and noise fields.

OBJECTIVES

The objective of this research is to understand the basic physics of low-frequency, broadband propagation and the effects of environmental variability on signal stability and coherence. In particular, it focuses on 3-D wave front coherence (horizontal, vertical, and temporal), on the details of signal energy redistribution through mode scattering, on signal and noise variability on ocean-basin scales, and on environmental processes such as internal waves that most affect long-range coherence.

APPROACH

The North Pacific Acoustic Laboratory (NPAL) program takes advantage of the acoustic network installed by the Acoustic Thermometry of Ocean Climate (ATOC) program, as well as instrumentation developed for that network and data previously obtained using it. ATOC network components have included two low-frequency (75 Hz), broadband acoustic sources installed on Pioneer Seamount off central California and north of Kauai, 14 U. S. Navy SOSUS arrays instrumented to receive the source transmissions, two autonomous vertical line arrays (AVLAs) installed near Hawaii and Kiritimati Island from November-December 1995 to August-September 1996, and an AVLA installed at OWS Papa from September 1998 to June 1999 (with NOPP funding). NPAL augmented the ATOC network with a sparse 2-D array installed at Sur Ridge off Point Sur, California, from July 1998 until August 1999 to receive the 3900-km-range transmissions from the Kauai source. The 2-D array consisted of four 700-m-long, 20-element vertical arrays and one 1400-m-long, 40-element vertical array, to allow measurement of the full 3-D signal wave front. The moorings were installed in a 3600-m line transverse to the acoustic path from the 75-Hz source north of Kauai. The data collected using the 2-D

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14. ABSTRACT
The ultimate limits of long-range sonar are imposed by ocean variability and the ambient sound field. Scattering from internal waves limits the temporal and spatial coherence of the received signal. Low frequency noise is dominated by shipping and by wave-breaking processes. The resulting ???granularity??? of the noise field can be exploited for detection and localization purposes. Our long-term objective is to understand the fundamental limits to signal processing imposed by these ocean processes, to enable advanced signal processing techniques, including matched field processing and other adaptive array processing methods, to capitalize on the three-dimensional character of the sound and noise fields.

15. SUBJECT TERMS

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array and U. S. Navy SOSUS receivers during the NPAL project are being combined with data previously collected by ATOC:

- To study the temporal, vertical, and horizontal coherence of long-range, low-frequency resolved rays and modes and to compare the measurements to predictions;
- To study scattering/diffusion effects (mode scattering, steep ray scattering);
- To study horizontal multipathing;
- To study the effects of bottom interaction at the source;
- To measure directional ambient sound spectra and noise granularity;
- To improve basin-scale ocean nowcasts via assimilation of average temperature derived from acoustic travel-time data and of other data types into models; and
- To determine environmental limitations on signal processing.

Extensive environmental measurements of the sound speed field between the Kauai source and the 2-D array were made (see below).

This research is a joint effort involving B. Cornuelle, M. Dzieciuch, W. Munk, and P. Worcester at the Scripps Institution of Oceanography (SIO) and R. Andrew, B. Dushaw, F. Henyey, B. Howe, J. Mercer, R. Spindel, and M. Wolfson at the Applied Physics Laboratory of the University of Washington (APL-UW). We are collaborating in the analyses with a large number of other investigators, including A. Baggeroer (MIT), M. Brown (UMiami), J. Colosi (WHOI), S. Flatté (UCSC), K. Heaney (Orincon), F. Tappert (UMiami), A. Voronovich (NOAA/ETL), and K. Wage (George Mason Univ.).

WORK COMPLETED

Field Work

Acoustic Source Operations. The Pioneer Seamount source transmitted at irregular intervals from December 1995 until December 1998. The source is no longer operable and has been abandoned in place, following a recovery attempt during August 2000 during which the source was damaged. The Kauai source transmitted from October 1997 until October 1999. Efforts to obtain the authorizations needed to transmit for another five years are currently underway (see below).

2-D Array Operations. The 2-D array was deployed on Sur Ridge during July 1998 and recovered during August 1999. All five of the AVLA's functioned satisfactorily throughout the year. The transmissions from the Kauai source are well above the ambient noise level at the 2-D array.

Environmental Observations. Two CTD/XBT/environmental mooring cruises were conducted during August 1998 and June 1999, while the 2-D array was in place, to provide direct measurements of the sound speed field and its spatial variability from gyre scales down to the scales of internal gravity waves on the acoustic path between the Kauai source and the 2-D array. In addition, two environmental moorings were installed between Kauai and the 2-D array on the first cruise and recovered on the second, instrumented with temperature, salinity, and velocity sensors, to provide information on the temporal variability of the sound-speed and current fields. A Seabeam 2000 multibeam system was used to measure bathymetry near the Kauai source, along the acoustic path, and near the 2-D array.

SOSUS Receiver Operations. Acquisition and archiving of ambient noise data from the SOSUS arrays continued throughout FY01.

Data Analysis

2-D Array Data (Signal). The receptions on the 2-D array are complicated by the fact that the sound interacts with the bottom near both the source and the receiver. Vertical beamforming has been used to filter the bottom interacting energy, allowing analysis of the fundamental acoustic properties of the resolved wave fronts (Fig. 1). Subband and subarray processing have been used to produce estimate of arrival times and vertical arrival angles of the resolved ray arrivals, and time-series of acoustic travel-times and angles have been developed. Data from all five AVLA's have been combined to determine horizontal arrival angles and to begin to examine the first and second order statistics of the horizontal wave fronts.

2-D Array Data (Noise). Shipping noise, earthquakes, and biologics have all been identified in the 2-D array data. Initial analyses of the statistics of the ambient noise field at the 2-D array have been completed.

SOSUS Receiver Data. Analysis of ambient noise data from the SOSUS receivers continued during FY01. Current ambient noise levels were compared with data collected 30 years earlier.

NPAL Data Analysis Workshops. The Second and Third NPAL Data Analysis Workshops were held during FY01. The Second NPAL Workshop was held in Leavenworth, Washington, on 5-6 October 2000, with 24 participants (Mercer, 2000). The Third NPAL Workshop was held in Chicago, Illinois, on 3 June 2001, with 20 participants (Worcester, 2001a). The Fourth NPAL Data Analysis Workshop is scheduled on 28-30 November 2001 in Borrego Springs, California.

Kauai Source Permitting Effort

The environmental review process required to obtain the authorizations needed to continue operation for five additional years of the low-frequency sound source previously installed off the north shore of Kauai, Hawaii, by the ATOC project made substantial progress during FY01. The reuse of the source for the NPAL project would combine (i) a second phase of research on the feasibility and value of large-scale acoustic thermometry, (ii) long-range underwater sound transmission studies; and (iii) marine mammal monitoring and studies. The Section 7 consultation under the Endangered Species Act was completed with issuance of the Biological Opinion on 26 April 2001, the NPAL Final Environmental Impact Statement was published in May 2001, the Hawaii Office of Planning issued a Consistency Certification for the NPAL project under the Coastal Zone Management Act on 23 July 2001, and the Final Rule under the Marine Mammal Protection Act was published on 17 August 2001. Barring unforeseen difficulties, we anticipate that the environmental review process will be completed by the end of 2001.

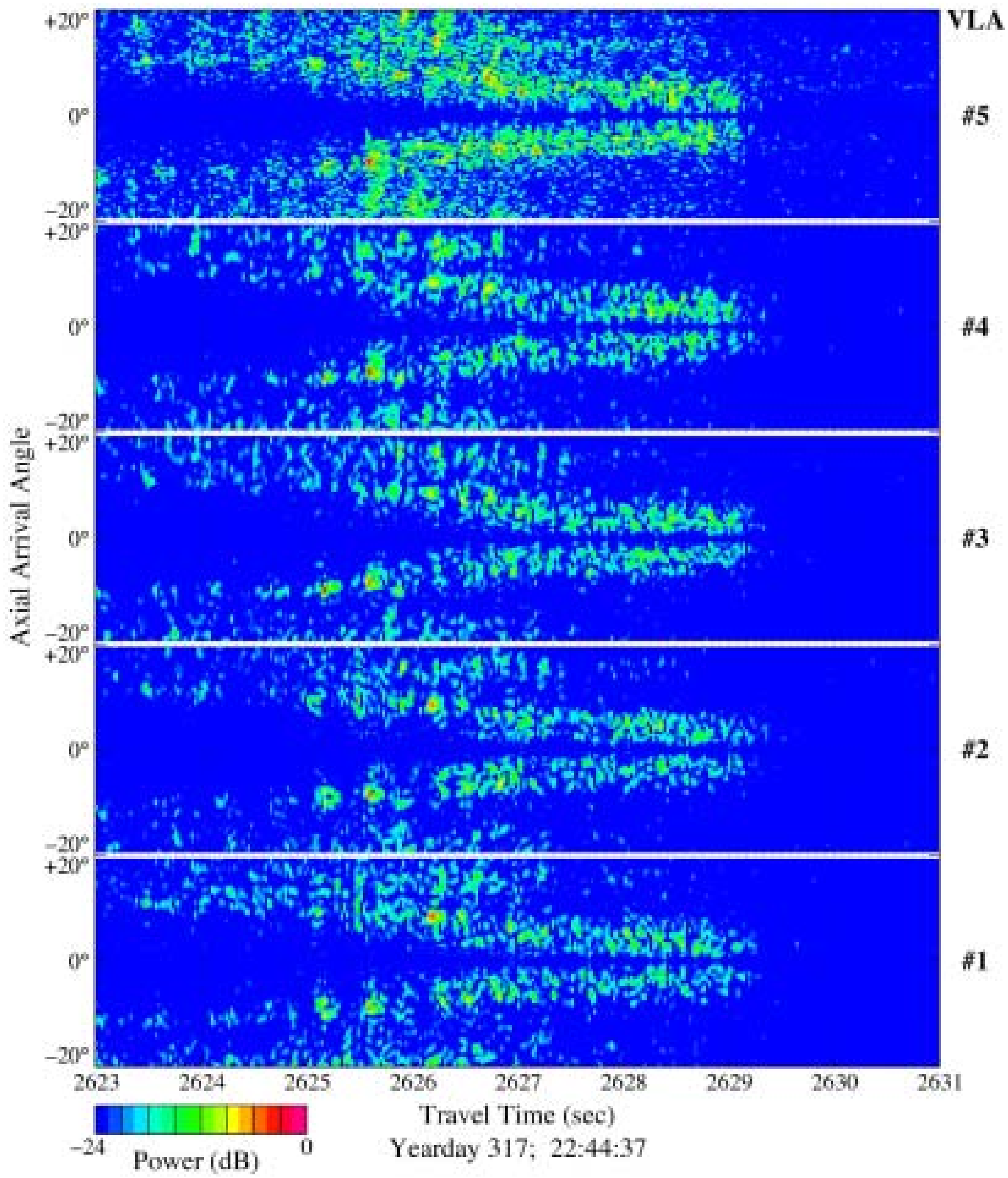

Fig. 1. Signal intensity plotted as a function of vertical arrival angle and arrival time for all five AVLA's in the 2-D array, after processing with a turning point filter (see below). Intensity peaks from similar arrivals are seen on all five arrays, indicating that the data can be combined to examine the variability of resolved ray arrivals. High angle arrivals (near 2627 sec.) are believed to be bottom reflections near the receiver.

RESULTS

*ATOC AVLA Data***.** Colosi *et al.* (2001a, b) continued analysis of intensity variability observed in the ATOC Acoustic Engineering Test. They found that (i) the signal statistics indicating weak scattering of the early ray arrivals are not sensitive to the integration time used in the signal processing, (ii) the intensity PDF's for identifiable wave fronts calculated using both integrated pulse energy and peak intensity are very closely log-normal, and (iii) on average 1.7 peaks per wave front segment per hydrophone were present, indicating significant wave front multipathing. The combined observation of weak scattering and multipathing is a novel result. Further, the scintillations in the finale, where no identifiable wave fronts are present, were found to be consistent with a near-exponential model, usually associated with full saturation.

2-D Array Data (Noise). Baggeroer *et al.* (2001) analyzed the first and second order statistics of the ambient noise field at the 2-D array, with the following results: (i) There is a wide spread in peak levels, most likely due to the proximity of shipping lanes. The maximum peak level in the recording band is 117 dB. (ii) Full broadband coherences tend to be low because of the presence of many ships. (iii) If one examines 1-2 Hz frequency bands, then lines of individual ships can be identified and associated. They are very coherent across the aperture. (iv) Vertical beamforming indicates relatively highly directional spectra at low grazing angles and a "noise notch" for the spectra at higher frequencies.

SOSUS Array Data (Noise). Andrew *et al.* (2001) compared ambient sound data obtained from a receiver on the continental slope west of Pt. Sur, California, with earlier measurements made during 1963–1965. They found that 1994–2000 levels exceed the 1963–1965 levels by 9 dB or less below 100 Hz and again at 250 Hz, but are roughly similar at 100 Hz.

Turning Point Filter. It has been customary to separate ray-based and mode-based analyses of acoustic data. Dzieciuch *et al*. (2001c) introduced the *turning-point filter* in an attempt to find a unified procedure which makes effective use of all the received energy. The method can be viewed either as an extension to linear beamforming, by accounting for ray curvature, or as modal horizontal wave number filtering with a vertical array. The technique was tested on the 28-Hz data from the dual-frequency Alternate Source Test.

Shadow-zone arrivals. Munk and Dzieciuch have modeled the scattering of sound into the shadow zone in long-range transmission by ocean processes other than internal waves (Munk, 2001). Microfrontal activity, in which density-compensated thermal (sound-speed) anomalies are found (often referred to as "spice," to distinguish this small-scale ocean variability from that due to internal waves), appears to be a significant factor.

IMPACT/APPLICATIONS

This research has the potential to affect the design of long-range acoustic systems, whether for acoustic remote sensing of the ocean interior or for other applications. The data from NPAL and ATOC indicate that existing systems do not begin to exploit the ultimate limits to acoustic coherence at long range in the ocean.

Estimates of basin-wide sound speed (temperature) fields obtained by the combination of acoustic, altimetric, and other data types with ocean general circulation models have the potential both to improve our ability to make the acoustic predictions needed for matched field and other sophisticated signal processing techniques and to improve our understanding of gyre-scale ocean variability on seasonal and longer time scales.

Using the World Ocean Atlas data base of 5 million temperature profiles and 1.4 million salinity profiles, Levitus *et al.* (2000) have produced the first compilation of global change in ocean fields. This covers the period 1948 to 1996. Even so, they were unable to document any changes at abyssal depths, 3 to 5 km, say; as the quality and quantity of data are insufficient for such an analysis. Yet such information is important for testing and improving existing coupled atmosphere/ocean models. Under favorable circumstances tomography can provide such information on the required millidegree precision, free of instrumental drift, and (once installed) on a continuing basis. Operating on a megameter scale, the underlying mesocale noise variance can be reduced by an order of magnitude.

TRANSITIONS

None

RELATED PROJECTS

(i) NPAL exploits the acoustic network, instrumentation, and data of the Acoustic Thermometry of Ocean Climate (ATOC) program (PI's: P. Worcester and R. Spindel, SERDP/DARPA/ONR). NPAL data continues to build the case for the role that acoustic methods can play in a large-scale ocean observing system. (Dushaw *et al.*, 2001a.)

(ii) NPAL also exploits data obtained as part of the dual-frequency Alternate Source Test performed for the "Ocean Acoustic Observatories" program. (PI's: Worcester, Mercer, and Spindel, ONR). (Worcester *et al.*, 2000a.)

(iii) A consortium led by R. Spindel was funded by the National Ocean Partnership Program to conduct research closely related to NPAL in response to a proposal entitled "Monitoring the North Pacific for Improved Ocean, Weather, and Climate Forecasts."

(iv) The ambient sound data collected as part of NPAL is being used in the ONR project "Baleen Whale Calls and Seasonal Ambient Noise" (PI's: J. Hildebrand, M. McDonald, and B. Howe).

(v) A consortium led by J. Orcutt was funded by the National Ocean Partnership Program to conduct research partially in support of NPAL objectives. The grant, entitled "Ocean Acoustic Observatory Federation," provides for limited maintenance and improvements to the San Nicholas Island and Barber's Point SOSUS receivers, as well as for deployment of acoustic data loggers near the Kauai source while it was transmitting as part of the Marine Mammal Research Program (Orcutt *et al.*, 2000). This effort also supported deployment of a 250-Hz acoustic source on Hoke Seamount off California for acoustic remote sensing of the California Current and the study of acoustic propagation through it (Han *et al.*, 2000).

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